GEOTHERM INC.
EARTH ENERGY CONSULTANTS & INSTRUMENTATION

TITLE: THERMAL PROPERTIES OF CONCRETES INCORPORATING SUPPLEMENTARY CEMENTING MATERIALS

FINAL REPORT

BY

GEOTHERM INC.

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GEOTHERM INC.

EARTH ENERGY CONSULTANTS & INSTRUMENTATION

28 MARCH 1988

Dept. Energy, Mines and Resources
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ATTN: Ms. V. Sivasundaram

THERMAL PROPERTIES TESTING OF CONCRETES INCORPORATING SUPPLEMENTARY CEMENTING MATERIALS (#23440-7-9137/01SQ)

Ten sets of concrete cylinders (nom.10cmx20cm),each consisting of three samples from the same batch, with metal probes cast in place were supplied by CANMET. Thermal testing was started after the age of 28 days of moist curing.

The thermal dryout curves (Figures 1 to 10), consisting of thermal conductivity and thermal diffusivity at 5 moisture levels ranging from fully saturated to completely dry, were obtained by oven drying the samples in stages. At each stage the samples were wrapped in plastic and allowed to come to moisture and temperature equilibrium prior to the thermal testing. The dry stage was obtained by leaving the concrete cylinders in the oven for 48 hours at 135°C.

The transient thermal probe method (EPRI EL-2128) was used to determine thermal conductivity (k)[W/°C-m] and the Shannon and Wells technique (ASTM Proc.,V47,p1044) to determine thermal diffusivity (α)[cm/s]. Papers describing these procedures and their theoretical basis are attached to the report. Please note that thermal conductivity (k) is the reciprocal of thermal resistivity (ρ)[°C-cm/W]. Conversions are as follows:

$$k\ [W/°C\text{-}m] = 100/\rho$$
$$k\ [BTU/°F\text{-}ft\text{-}h] = 1/(\rho \times 0.0173)$$
$$k\ [mcal/°C\text{-}cm\text{-}s] = 1/(\rho \times 0.004187)$$

Finally the specific heat of dry material chipped from each concrete specimen was determined using a calorimeter.

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Thermal testing was carried out using the GEOTHERM TPA-5000, a system that fully automates the transient thermal probe test. It is micro-computer controlled and provides programmable power to thermal probes, reads temperature sensors, probe current and voltage, and progressively computes the thermal conductivity during the test. The unit consists of a programmable 10 amp, 60 volt power supply, a 10 channel data aquisition system and an HP-85B micro-computer. A nominal 110 volt power source is required. The entire test procedure is software controlled in a totally interactive manner so that programming experience is not required by the operator. Various built-in error reducing features ensure that the test complies with the theoretical assumptions of the line heat source theory. A statistical analysis of data indicates whether an acceptable test has been accomplished. Test data (time, temperature, power) are printed, plotted and stored on tape so that future analysis and reference to the results may be made.

The thermal conductivity depends on many variables, including: concrete composition, moisture content, density, and temperature. For practical purposes the variation due to changes in ambient temperature is very slight and may be ignored. It is only of importance if the concrete freezes, in which case the conductivity may increase appreciably. The attached thermal dryout curves show the variations of conductivity with moisture content for each set of concrete samples. Thus any variations in conductivity between sets should be attributed to differences in composition and dry density.

Figure 11 shows all the thermal dryout curves on one plot. At low moisture contents the conductivity appears to be a function of the dry density with the higher conductivities attained by the denser concretes.(Please note that dry densities were calculated using the dry concrete cylinder weight and nominal volume from the 10cm x 20 cm cylinder dimensions.) At saturation moistures most of the conductivities tend to fall between 2.12 and 2.22 W/°C-m, although #4 and #10 are slightly higher at 2.33 and 2.38 W/°C-m and #7 and #8 lower at 2.00 and 1.92 W/°C-m respectively. A general density relationship exists although the concrete composition may also influence the conductivity.

The specific heats of the dry concrete were quite consistent and overall were quite close to 0.17. Therefore,since the heat capacity, conductivity and diffusivity are inter-related, the diffusivity vs. moisture curves follow the same trends as the conductivity curves.

Should you have any questions or require further information, please do not hesitate to contact us.

GEOTHERM

J.E.Steinmanis, P.Eng.

FIGURE 1

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THERMAL DRYOUT CURVES

SAMPLE: TT1R

SPECIFIC HEAT (DRY) 0.170

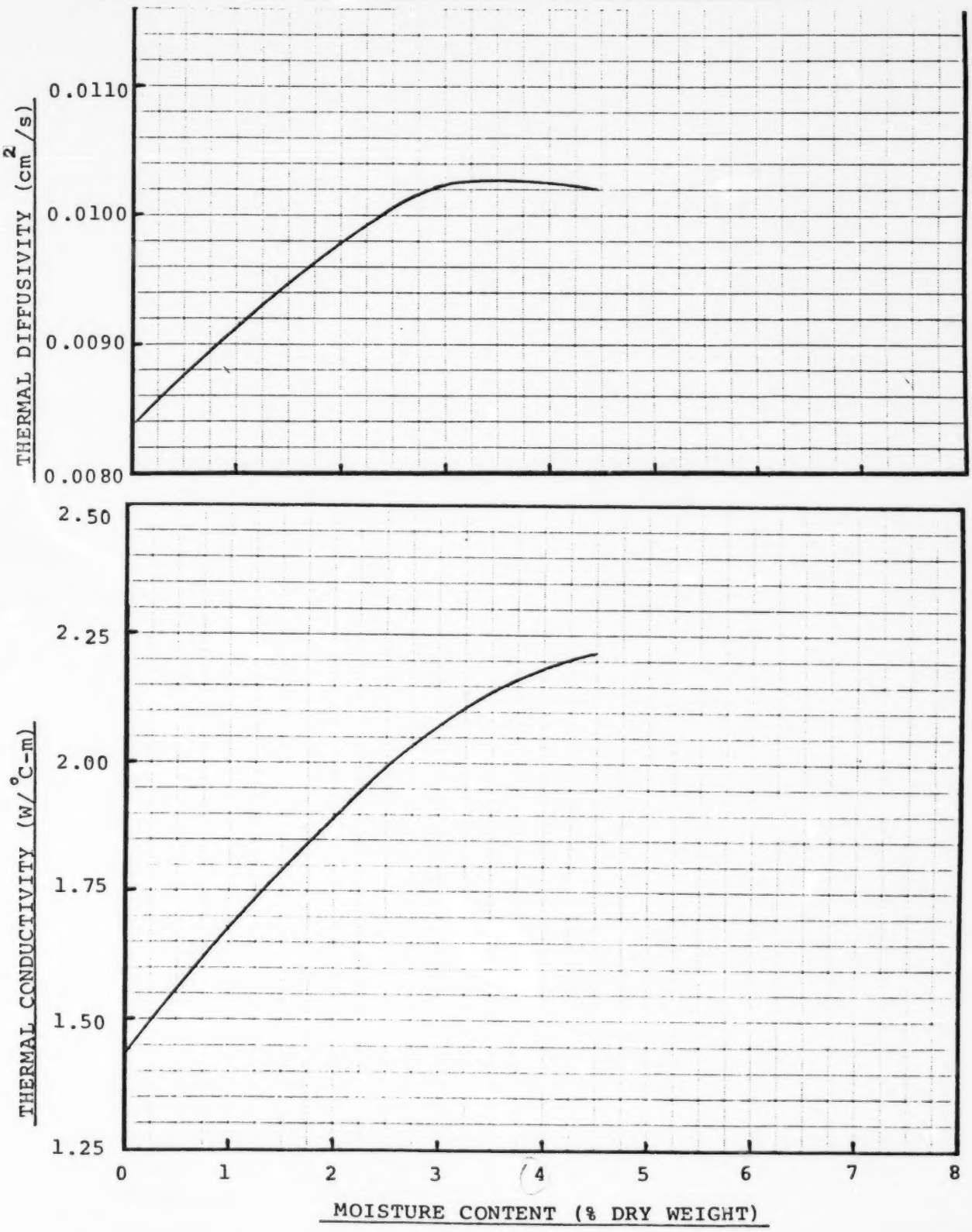

FIGURE 2

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THERMAL DRYOUT CURVES

SAMPLE: TT2 SPECIFIC HEAT (DRY) 0.171

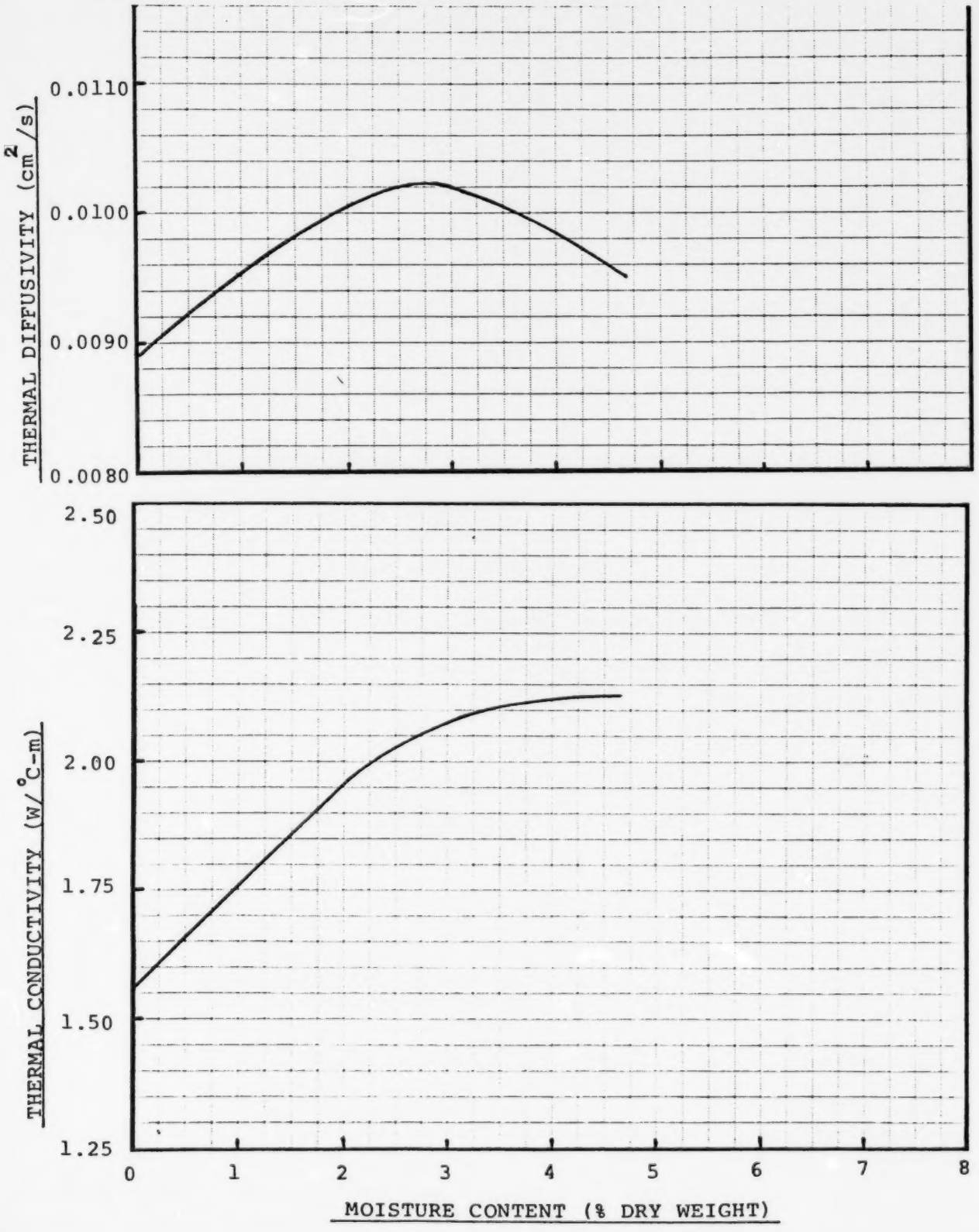

FIGURE 3

DATE: March 1988

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THERMAL DRYOUT CURVES

SAMPLE: TT3R

SPECIFIC HEAT (DRY) 0.165

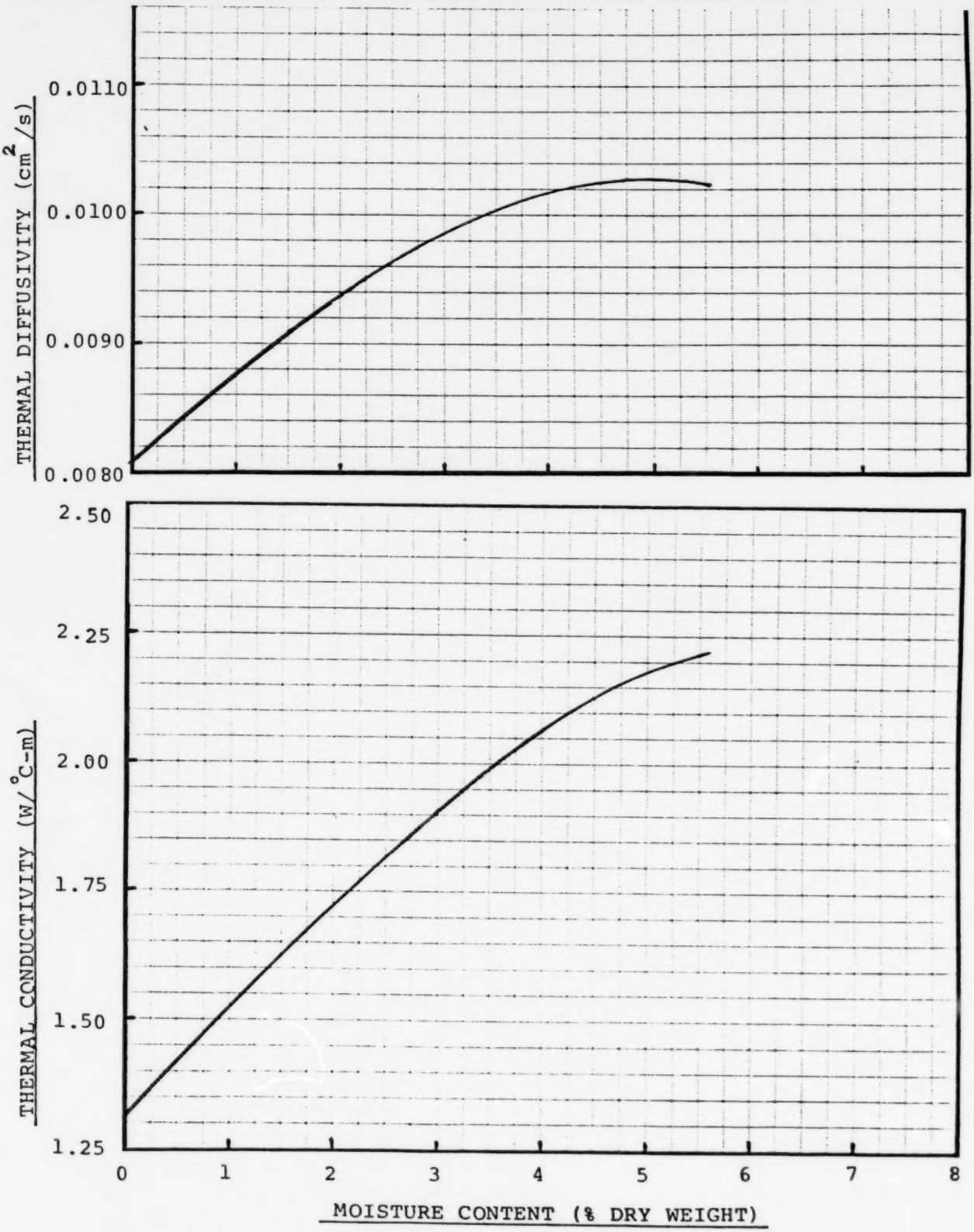

FIGURE 4

DATE: March 1988

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THERMAL DRYOUT CURVES

SAMPLE: TT4R SPECIFIC HEAT (DRY) 0.170

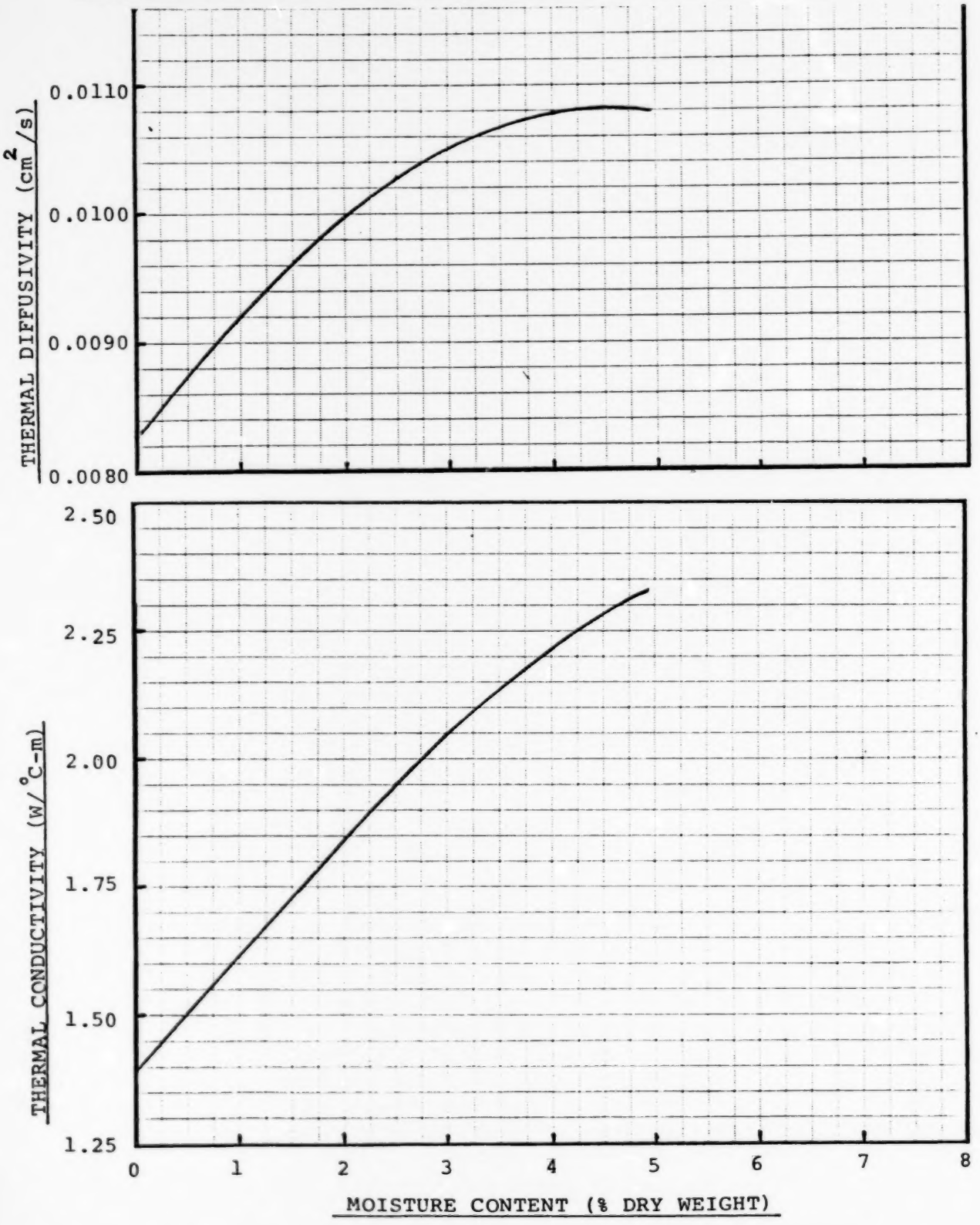

FIGURE 5

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THERMAL DRYOUT CURVES

SAMPLE: TT5 SPECIFIC HEAT (DRY) 0.169

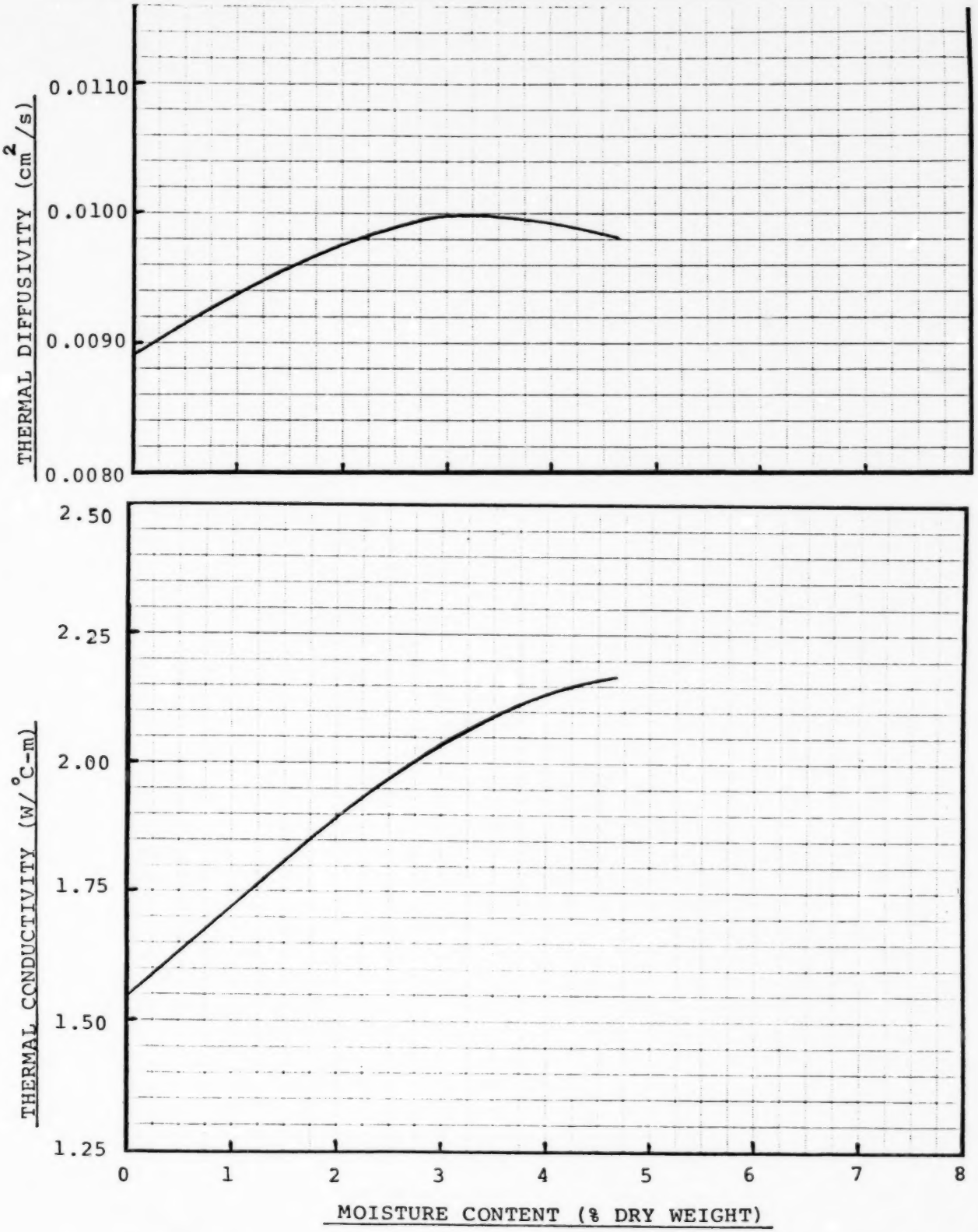

FIGURE 6

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DATE: March 1988

THERMAL DRYOUT CURVES

SAMPLE: TT6R SPECIFIC HEAT (DRY) 0.164

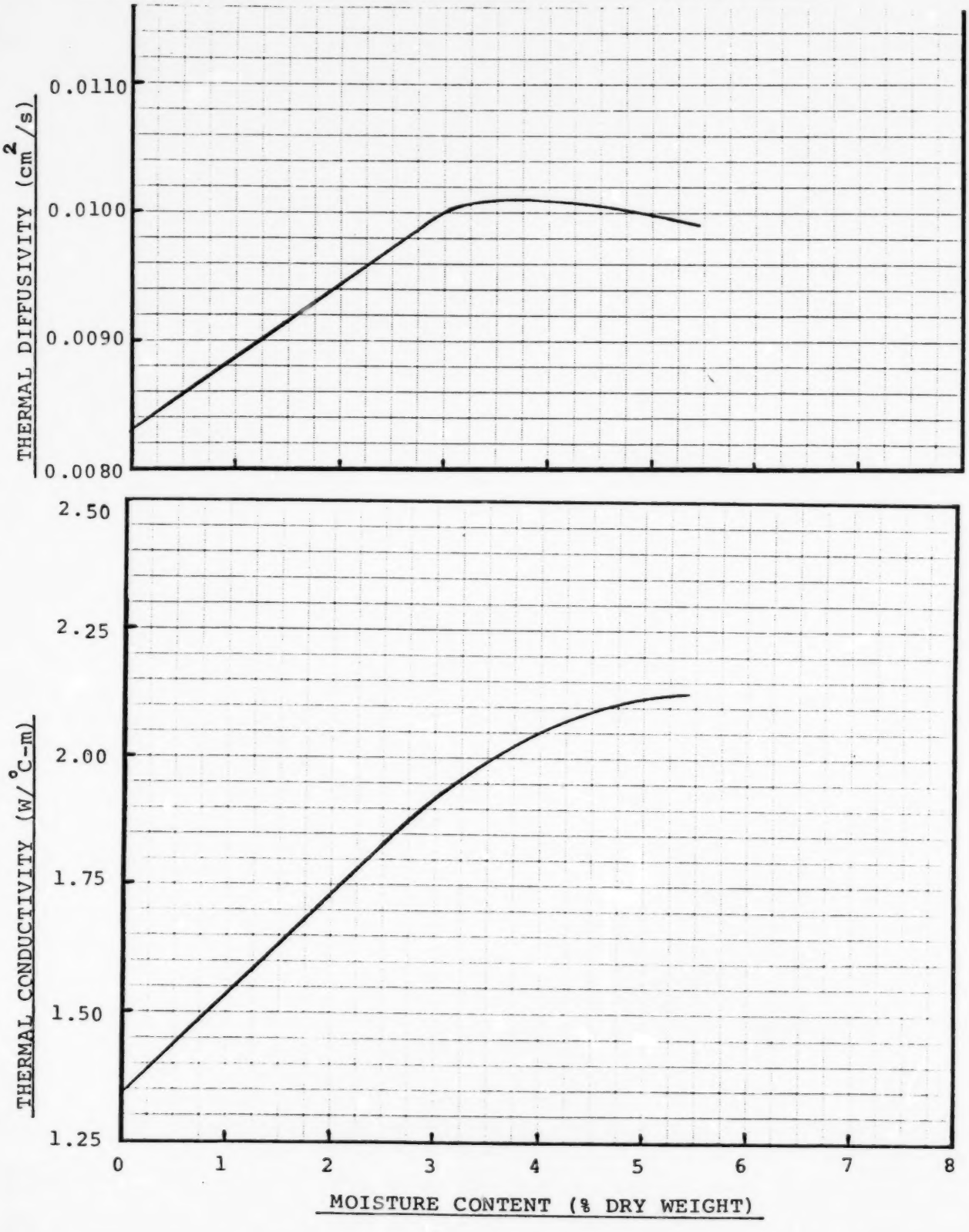

FIGURE 7

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THERMAL DRYOUT CURVES

SAMPLE: TT7 SPECIFIC HEAT (DRY) 0.164

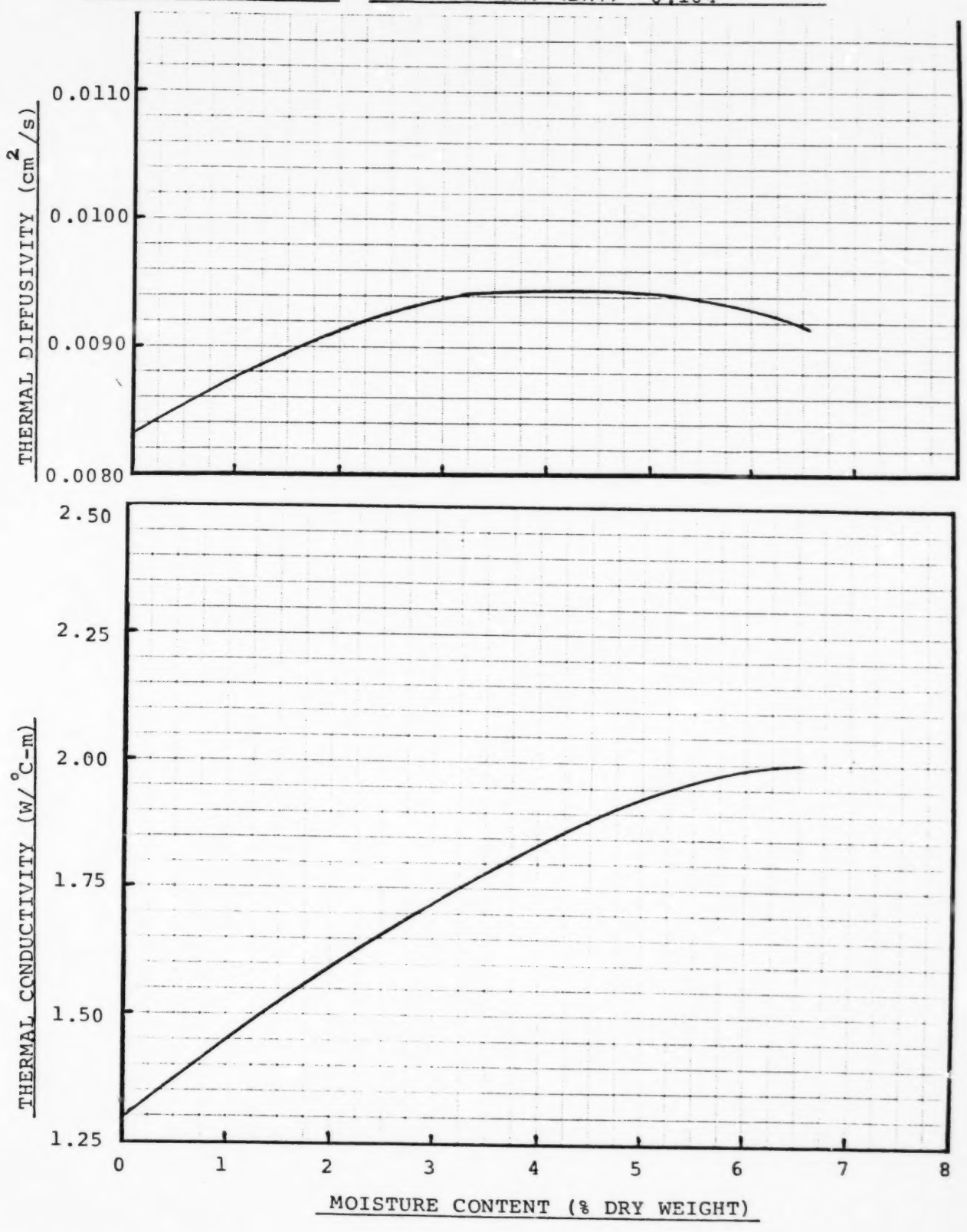

FIGURE 8

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THERMAL DRYOUT CURVES

SAMPLE: TT8 SPECIFIC HEAT (DRY) 0.172

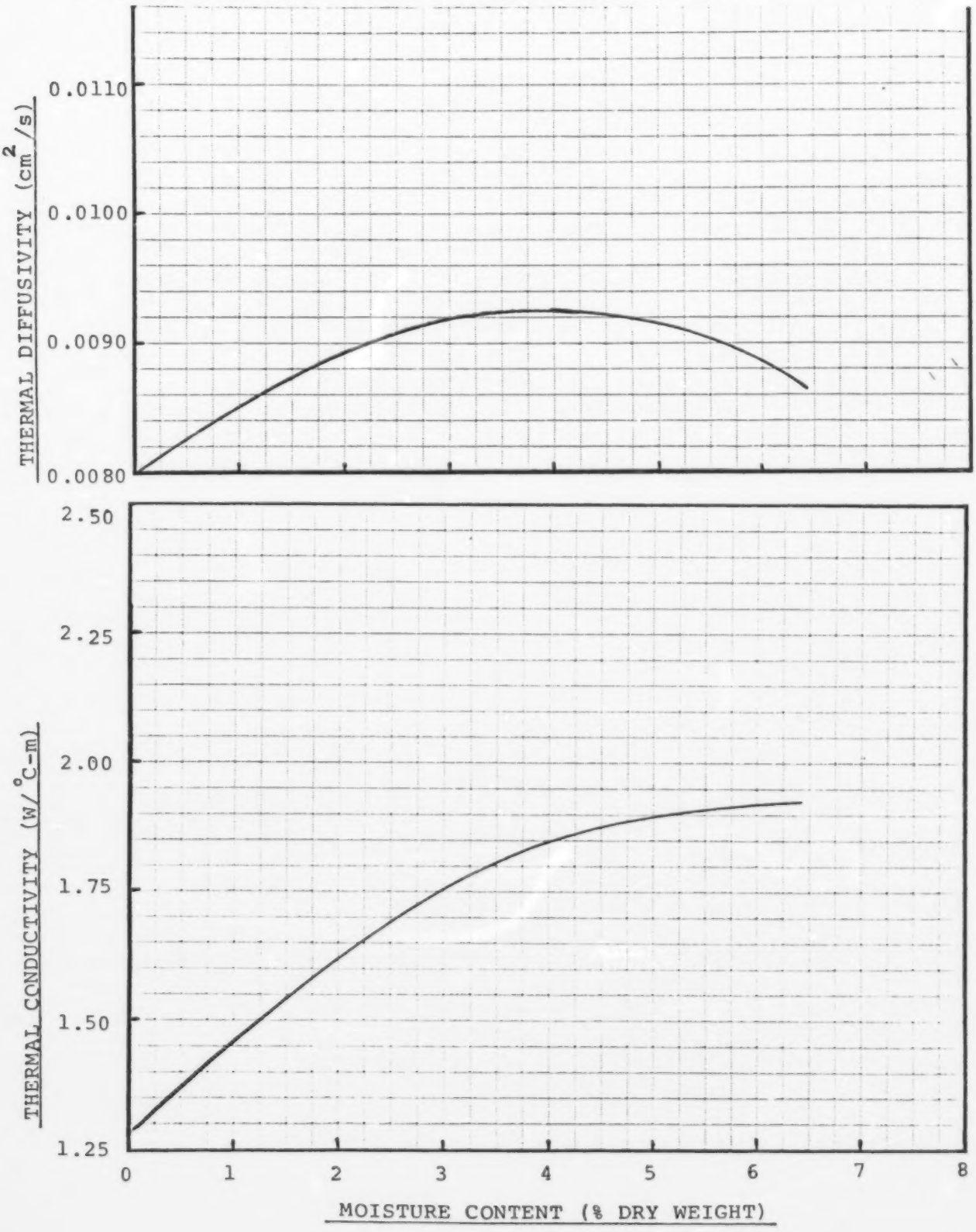

FIGURE 9

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THERMAL DRYOUT CURVES

SAMPLE: TT9 SPECIFIC HEAT (DRY) 0.178

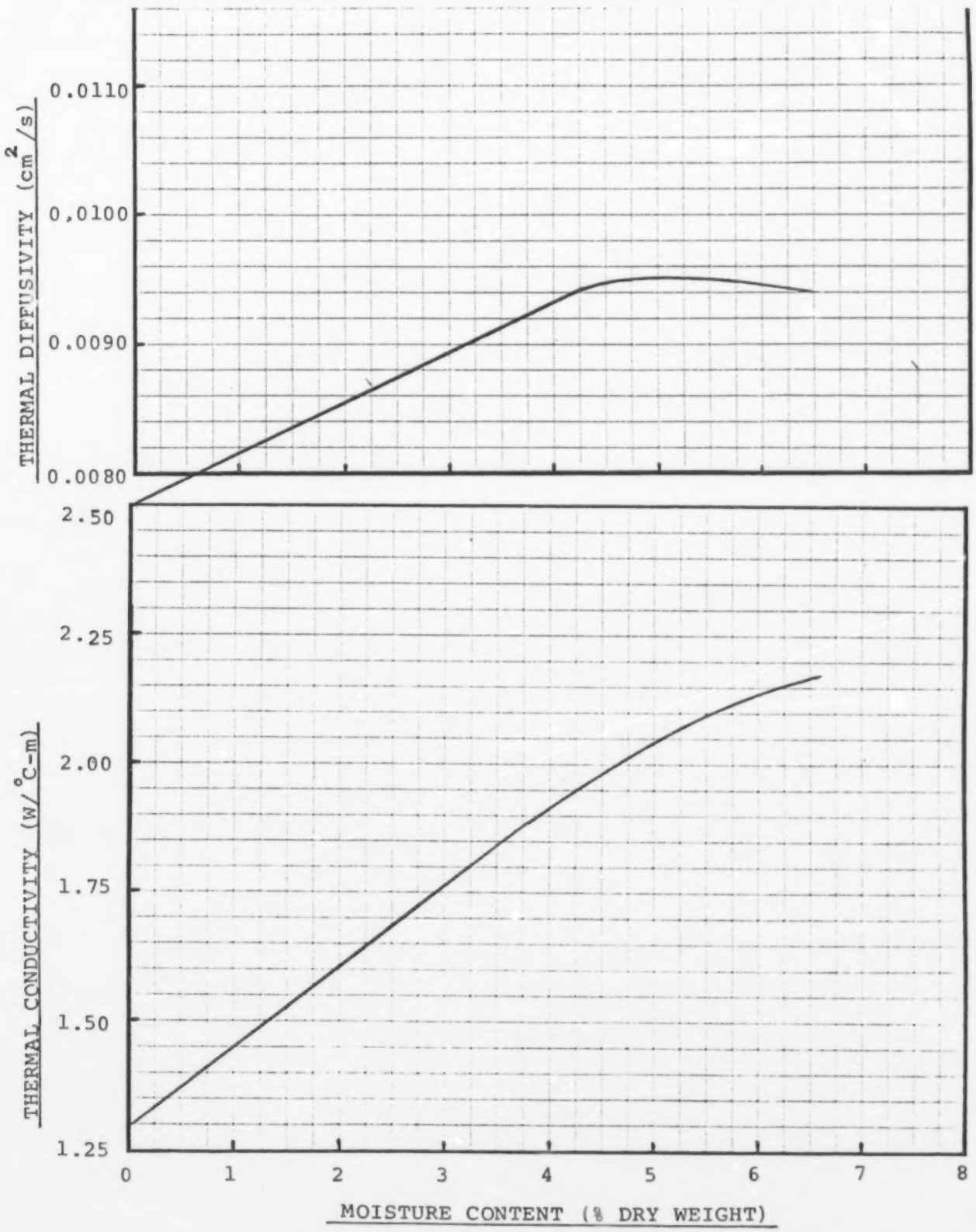

FIGURE 10

DATE: March 1988

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THERMAL DRYOUT CURVES

SAMPLE: TT10 SPECIFIC HEAT (DRY) 0.172

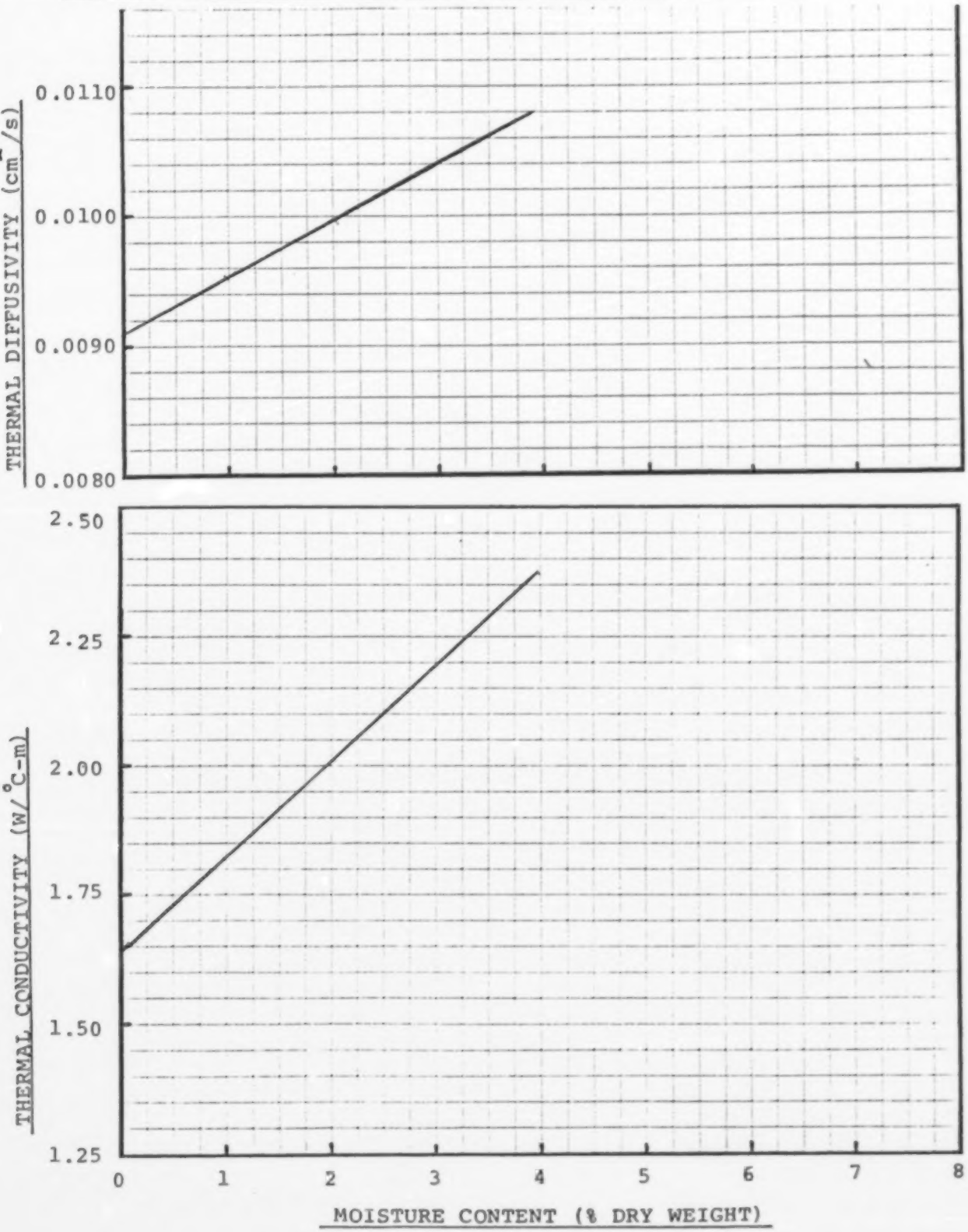

FIGURE 11

DATE : March 1988

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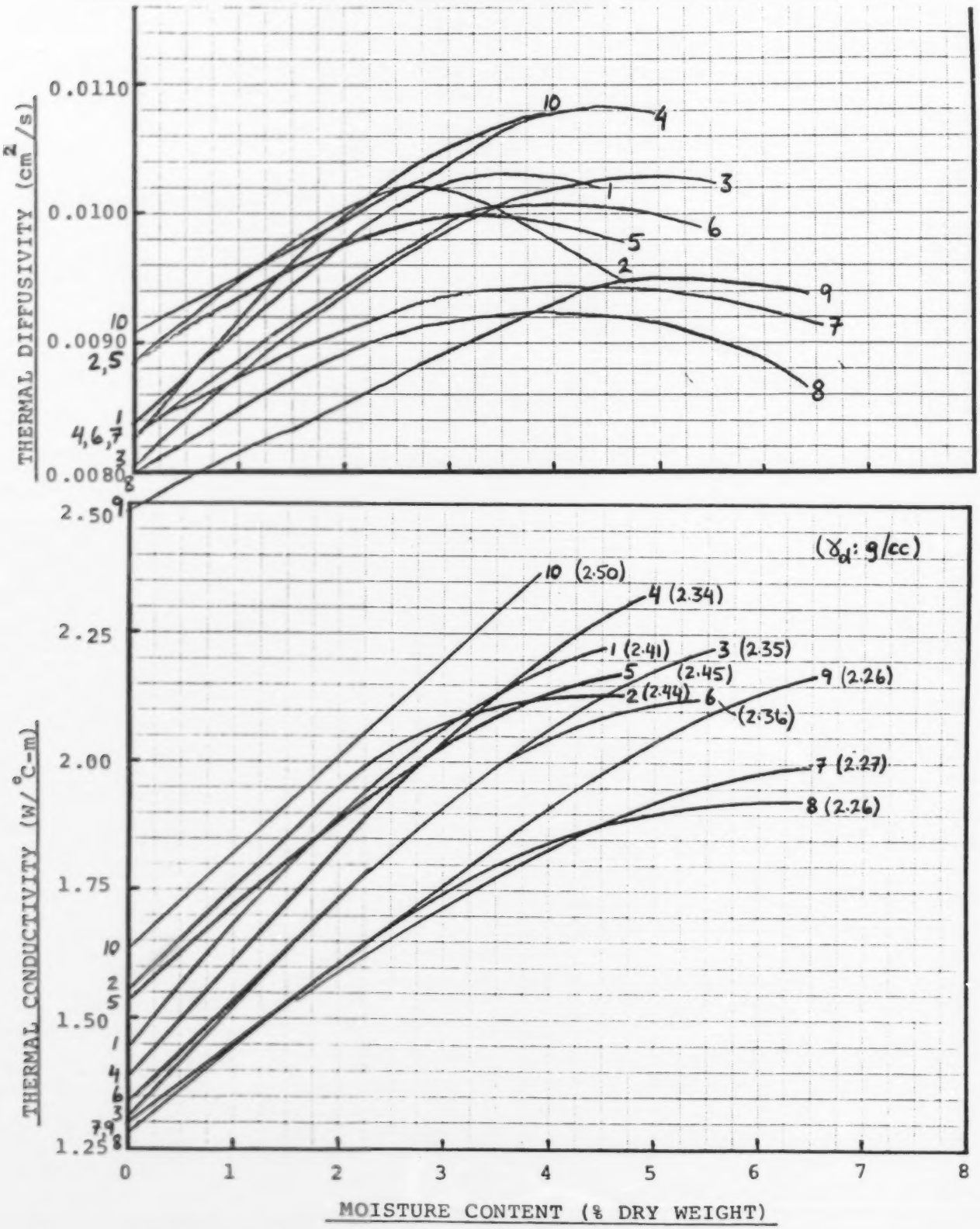
THERMAL DRYOUT CURVES

SAMPLE: SPECIFIC HEAT (DRY)



Underground Cable Thermal Backfill

Pergamon Press, Toronto, 1982

THERMAL PROPERTY MEASUREMENTS USING A THERMAL PROBE

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ABSTRACT

The transient thermal probe is a relatively quick method of measuring soil thermal properties. Accurate test results can be obtained with correct test procedures, proper probe construction and calibration, and an understanding of the limitations of the transient thermal probe method. Undisturbed Shelby tube soil samples can be used for laboratory testing. The transient thermal probe method is used to determine thermal resistivity, and the Shannon and Wells method to determine thermal diffusivity. The use of large diameter probes for field thermal testing requires even greater consideration of theoretical assumptions.

KEYWORDS

Soil thermal property measurements; thermal resistivity; thermal diffusivity; transient thermal probe method.

INTRODUCTION

The transient thermal probe is a relatively quick method of measuring the thermal properties of soils and gives accurate results provided the theoretical assumptions are understood and care is taken in the test set-up to stay within the realm of the theory. The transient method has the advantage over steady state methods that a single measurement can give not only the thermal resistivity but also the thermal diffusivity and thermal stability (Boggs and others, 1980).

The transient probe method is based on the theory of the infinite line heat source (Carslaw and Jaeger, 1959) which predicts that the temperature as a function of time at a distance "r" from an infinite-line heat source dissipating "q" power per unit length into a medium of thermal resistivity "ρ" and thermal diffusivity "α" is:

$$T(t) = \frac{-q\rho}{4\pi} \, Ei \left(\frac{-r^2}{4\alpha t}\right) \qquad (1)$$

which can be expanded in the form:

$$T(t) = \frac{-q\rho}{4\pi} \left[\ln \frac{4\alpha t}{r^2} - \gamma + \frac{r^2}{4\alpha t} - \frac{1}{4}\left(\frac{r^2}{4\alpha t}\right)^2 + \frac{1}{9}\left(\frac{r^2}{4\alpha t}\right)^3 - \frac{1}{16}\left(\frac{r^2}{4\alpha t}\right)^{4+} \ldots\right] \qquad (2)$$

where γ is Euler's constant 0.5772

If only the first term is kept, one obtains:

$$T(t) = \frac{q\rho}{4\pi} \left[\ln \left(\frac{4\alpha t}{r^2}\right) - \gamma\right] \tag{3}$$

which can be rearranged in the form:

$$T(t) = \frac{q\rho}{4\pi} \left[\ln t + \ln \frac{4\alpha}{r^2} - \gamma\right] \tag{4}$$

from which it becomes apparent that if temperature is plotted as a function of ln(t), the slope is $q\rho/4\pi$, from which the thermal resistivity can be determined. (Fig. 1)

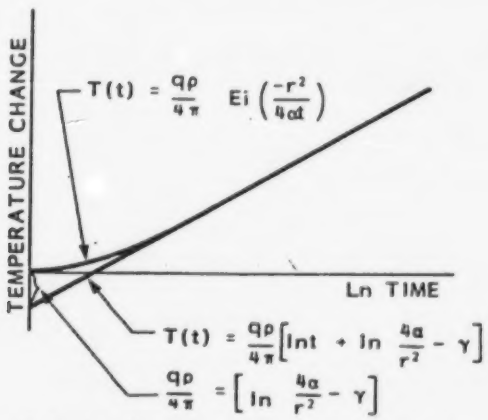


Fig. 1 Relation between temperature rise, time, and soil thermal parameters

Blackwell (1954) developed an approximate solution for a hollow cylindrical probe which is very close to the line heat source equation:

$$T(t) = \frac{q\rho}{4\pi} \left[\ln t + \ln \frac{4\alpha}{r^2} - \gamma + \frac{2}{\rho r H}\right] \tag{5}$$

where H is the contact conductance at the probe-soil interface.

From the above, the thermal diffusivity may be obtained by the intercept method. If I is the intercept of the straight line extrapolated back to the ln t axis, then:

$$\alpha = \frac{r^2}{4} \exp \left[\gamma - \frac{2}{rH\rho} - I\right] \tag{6}$$

To a first approximation, the term $2/rH\rho$ can be ignored if a large radius probe is used and the contact between the soil and the probe is good.

For test results to agree with the above theoretical predictions the experimental procedures should comply with the major assumptions, namely:

i) the probe is an instantaneous and constant source of heat

ii) flow of heat is radial

iii) test data is free from the sample boundary effects

iv) no thermal contact resistance exists between the heat source and the soil

v) conduction is the only mechanism of heat transfer

vi) test material is homogeneous, and a moisture and thermal equilibrium exists in the sample before the test.

EQUIPMENT

The criteria of constant and true cylindrical source of heat are better approximated with the use of quality equipment. The major components of the equipment package are the power supply, the temperature reader, and the thermal probe.

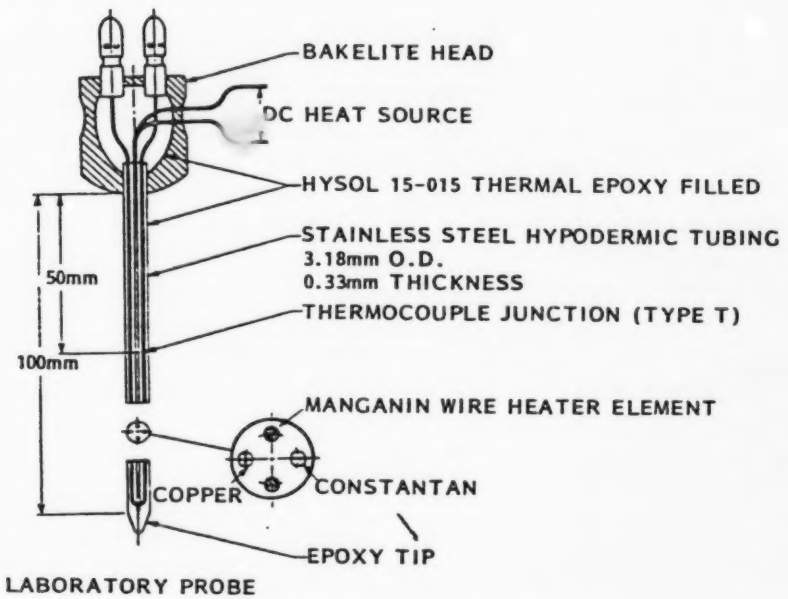
Mitchell and Kao (1978) demonstrate the effect of an unstable current source. They indicate that a small variation (1-2%) in the current output from the power supply can have a large effect on the thermal resistivity (-18%). Their concern is with the use of storage batteries which can have variations in the current output. Our experience is that a good quality stabilized DC power supply run off an AC generator in the field, or AC main line in the laboratory is able to deliver constant current.

A temperature reader (thermocouple reader in most cases) that drifts excessively due to environmental conditions (heat, air current) will produce inconsistent results. In field applications it is especially important that the thermocouple reader be shielded from environmental effects since the sun's heat may cause a drift in the isothermal reference junction in the compensation circuitry. In laboratory applications a properly maintained ice bath reference for the thermocouples gives the most consistent results.

Any shortcomings in the equipment are magnified in the field where conditions are harsher than in the laboratory environment. Ontario Hydro uses the Thermal Property Analyzer (Boggs and others, 1980), which is a microprocessor controlled unit that provides a stable power source and stable thermocouple readings in addition to automating the whole process of running a thermal resistivity test.

A properly constructed thermal probe is essential and exacting standards are to be met with regards to: thermocouple placement, uniformity of cross section along the length of the probe, proper insulation against electrical shorts, heater resistance and length measurements, and mechanical durability. Wechsler (1966) investigated the design of the thermal probe and made recommendations about the construction technique. The probes used by Ontario Hydro (Fig. 2) are similar to these. It is important to note that the heater should be as close to the sheath as possible, with the measuring thermocouple also located at the interior wall of the sheath. An epoxy filler of low thermal resistivity minimizes the initial transient time to valid test points. A stainless steel sheath provides good structural rigidity as well as minimizing interference with radial heat flow.

In order to ensure that axial heat flow is insignificant for the duration of the test, the probes must have a sufficient length to diameter ratio. Blackwell (1954) provides the methodology for choosing an appropriate ratio based on his theoretical analysis.



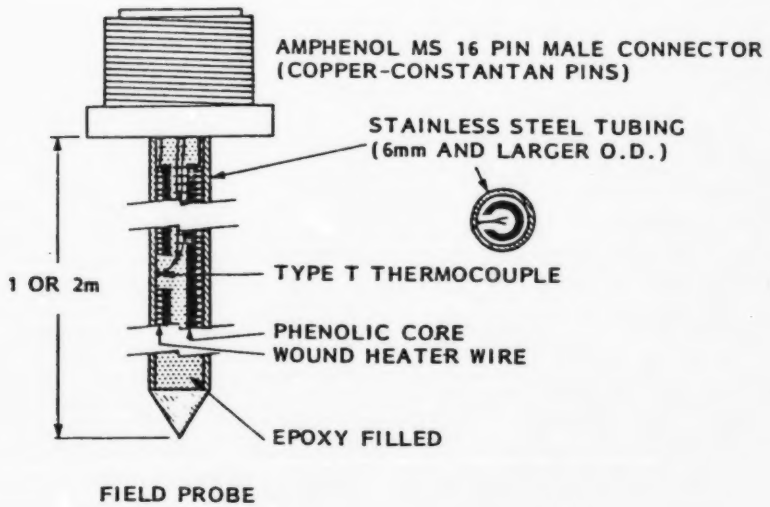


Fig. 2 Thermal probes

CALIBRATIONS

Several checks and calibrations are to be performed on the probes to validate them for use. The total resistance of the heater should be measured and compared to that specified. If it is not as expected, it will result in an incorrect calculation of probe power, and thus thermal resistivity. Resistance can be determined by external measurement, but the heater length cannot be assumed the same as the probe length. The length of the heater can be determined by attaching external thermocouples, heating the probe, and noting at which point the temperature ceases to rise dramatically. Checks for heater-thermocouple and heater-sheath shorts are simple, and resistances between the above components should exceed 10 kΩ.

The thermal probes can be calibrated in laboratory standard materials, such as glycerol, or against other standard techniques, such as the guarded hot plate (ASTM C177). The advantages of glycerol are twofold. Being a liquid, the probe thermal contact is extremely good and contact resistance-related errors can be neglected. Also, since glycerol is viscous, convective heat flow is negligible as long as the test temperature rise is kept small (less the 5°C). The experimental result may be compared to the published value (349°C-cm/W at 20°C) and any discrepancy can be corrected with a multiplying factor. Furthermore, calibration liquids can be found to cover the expected range of soil thermal resistivities.

If the internal thermocouples are not in perfect contact with the probe sheath, the actual probe radius may not be the correct parameter to use in the intercept method of thermal diffusivity calculation. The 'effective radius' of a probe may be determined by using the temperature versus time data for a glycerol run in the TDFIT computer program (Boggs and others, 1980) and varying the probe radius until the calculated thermal diffusivity matches the published value for glycerol (9.4×10^{-4} cm^2/sec at 20°C). The TDFIT program, which was developed by Ontario Hydro, is based on Blackwell's (1954) solution of the heat diffusion equation for a cylindrical probe having finite heat capacity and contact conductance.

The probe heat capacity can be determined from a very low power thermal resistivity run (less than 1 C° temperature rise over 500 seconds) in a good thermal insulator such as foam rubber. Now from the straight line portion of the temperature vs time (not log time) plot:

$$C = \text{POWER} \times \frac{\Delta \text{time}}{\Delta \text{temp}}$$

High probe heat capacity may cause excessively long initial transient times.

PROBE TO SOIL THERMAL CONTACT RESISTANCE

When a probe is inserted in an undisturbed sample, the probe to soil contact becomes an important factor. In practice, the major deviation from the theoretical probe response is caused by the thermal contact between the probe and soil. If the probe had no heat capacity, this would cause only an instantaneous offset in the temperature when probe power is initiated. Because of probe heat capacity, the contact-related temperature rise gradually approaches the offset value. Whereas the effect of probe heat capacity is predictable, the contact conductance depends on the soil under test and the skill of the operator in installing the probe with minimum disturbance. The diameter of the thermal probe can affect the magnitude of the thermal contact resistance effects. That is, for the same given amount of disturbance, a smaller diameter probe will "see" a larger volume of voids relative to its surface area, therefore the time to overcome the contact disturbance will be greater.

Poor probe to soil contact results in a longer time to approach the straight line portion of the curve (ie initial transient time). For the determination of ther-

mal resistivity this will delay the formation of the straight line portion of the data, but not change the absolute value of the thermal resistivity which is derived from the slope of that straight line (Fig. 3). However, for the thermal diffusivity determination with the intercept method, the contact resistance offset is crucial, because the diffusivity depends on both the slope and intercept. Only if the probe radius is sufficiently large, and the contact is good, can the intercept method give a reasonable value of thermal diffusivity.

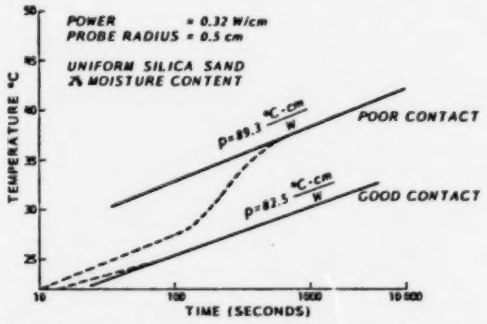


Fig. 3 The effect of probe to soil thermal contact resistance on the determination of soil thermal resistivity and diffusivity

LABORATORY THERMAL RESISTIVITY TEST

In the laboratory, Ontario Hydro attempts to simulate field conditions, therefore the standard procedure is to retrieve relatively undisturbed tube samples of soil rather than loose samples that have to be reconstituted for a test. The 76 mm (2-7/8 inch) diameter Shelby tube sample has proven to be sufficient for our applications and efforts in standardizing testing procedures have been based on it. From a single set-up it is possible to run the transient thermal resistivity test and the Shannon and Wells thermal diffusivity test.

In relatively homogeneous Shelby samples the 3.2 mm (1/8 inch) diameter needle works well in that it has fairly good strength for pushing into stiff materials and contact problems are usually of a manageable magnitude. While a smaller diameter needle, such as 1.6 mm (1/16 inch), has a greater chance for poor thermal contact it has an advantage in materials that contain stone size particles (such as tills). In this case the finer needle may slip in more easily between the larger stones, whereas the larger probe may catch on these particles and not be able to be inserted at all.

In softer soils a needle can be inserted by hand. In variable soils it is difficult to hold the probe steady and a large amount of distortion in the hole may occur. In practice, the probes should be held by a jig that will keep everything stable while the probe is pushed in. In very stiff soils, it may be necessary to drill a pilot hole; however, the resulting probe to soil thermal contact is usually poor. Care must be taken to ensure that small probes are not inadvertently moved during a test, resulting in distortion of the thermal field and invalid data.

Even if exceptionally good contact is achieved, say by packing the soil around the probe, an initial transient will be evident in the temperature vs log time curve due to probe properties such as; finite diameter, thermal resistivity and heat capacity of the probe materials. Hartley and Black (1976) have produced curves,

based on Blackwell's theory, that indicate minimum transient times taking the above factors into consideration. Of course, poor probe to soil contact will result in a much longer time but these calculated transient times along with estimates of sample boundary time effects can be used as an aid in selecting the portion of the experimental curves to use for thermal resistivity calculations.

SAMPLE BOUNDARY EFFECTS

The theory for the transient thermal resistivity test is based on an infinite sample size, therefore if a sample of given radius is used boundary effects will become evident after a certain time. The actual test results must be separated from these effects. According to de Vries and Peck (1958), this time can be estimated from

$$\exp\ (-\ R^2/4\alpha t) \ll \phi \qquad (7)$$

where R = sample radius
α = sample diffusivity
t = time
ϕ is $\ll 1$, say 0.02 (Wechsler, 1966).

In practice this appears to give the time when the thermal front first impinges on the boundary. It takes a longer time for these boundary effects to cause a deviation at the thermal probe. By placing a thermocouple at the soil-container boundary and monitoring it along with the thermocouple in the probe the relationship between theoretical calculation, test effect, and boundary effect may be observed (Fig. 4). The 76 mm diameter tube sample has proved to be sufficient for materials with thermal resistivities greater than about 45°C-cm/W (ie as thermal resistivity increases, the time for the boundary effects to invalidate the results becomes longer). The value of 45°C-cm/W is based on the fact that the initial transient time before the straight line may be 200 to 300 seconds and for a 76 mm Shelby tube the edge effects become evident at about 700 to 800 seconds. At lower thermal resistivities the initial transient time and boundary effects time may become too close to choose a proper straight line for the thermal resistivity calculation.

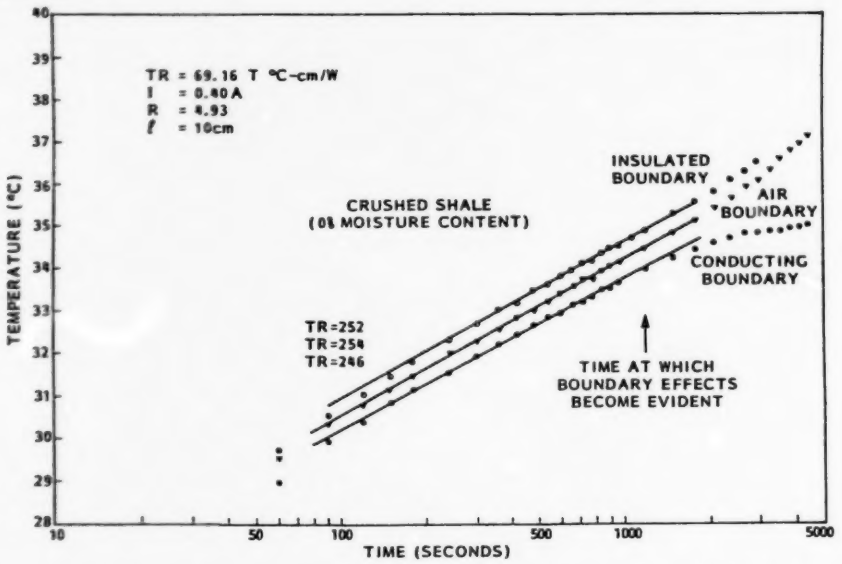


Fig. 4 Boundary effects on thermal resistivity tests in Shelby tube samples

It is helpful to know the effects of different boundary conditions on the experimental curve. The temperature vs time curve swings upwards if the boundary is insulated whereas it levels off for a conducting boundary (such as a stirred water bath). Air behaves like an insulating boundary. The thermal resistivities determined from the straight line portion of the test data for each of the boundary conditions are fairly close (Fig 4).

STAGE DRYING TEST

A discrete thermal resistivity at a particular moisture content is insufficient information for most applications as in situ soil moisture and thus thermal resistivity continually change. A stage drying test must be performed on the Shelby tube samples to fully characterize the thermal behaviour of the soil. Figure 5 shows characteristic curves of thermal resistivity vs moisture content for different types of soils.

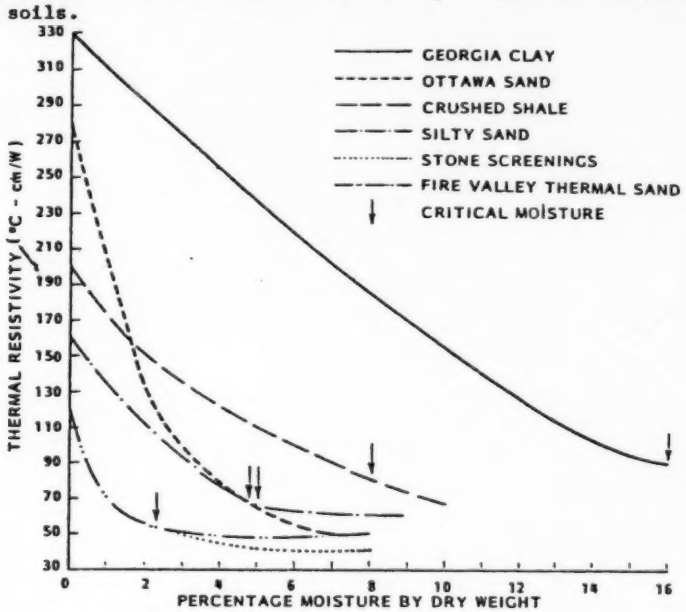


Fig. 5 Thermal resistivity vs moisture content

The sample and tube may be cut into sections in order to measure the thermal resistivity as a function of depth. The laboratory probe is left inserted and the sample air and oven dried in stages to obtain the thermal resistivity as a function of moisture content. After each drying stage the sample must be sealed (plastic wrap) and allowed to cool (if oven dried), and equilibrate with respect to spatial moisture distribution (requiring several hours for a granular soil, at least overnight for silty soils, and even longer for clayey soils) prior to measuring thermal resistivity.

The importance of sample equilibrium cannot be over-emphasized. If a sample is moved from a cooler to warmer environment it must be given time to come to ambient conditions. This can be monitored with the thermal probe. The samples must be wrapped in plastic because surface evaporation during a test may cause enough cooling to give erroneous results.

The amount of input power to the probe and hence the soil must be carefully selected to insure that conduction is the only mechanism of heat transfer. If the

probe heats up too much, moisture migration will be induced. Conversely if there is too small a temperature rise there will not be a clear definition in the experimental curve. In general, the standard 1000 second thermal resistivity test should have a total temperature rise above ambient of about 6 to 10 C°.

SHANNON AND WELLS THERMAL DIFFUSIVITY TEST

The Shannon and Wells thermal diffusivity test was adapted for use with Shelby tube (76 mm) samples using a thermal probe as the passive temperature sensor. This type of set-up would allow tests to be carried out on an undisturbed sample for both thermal resistivity and thermal diffusivity. The Shelby tube samples are prepared as in Fig. 6. Care must be taken to centre the thermal probe and to seal the tube ends properly since the sample will be immersed in a water bath.

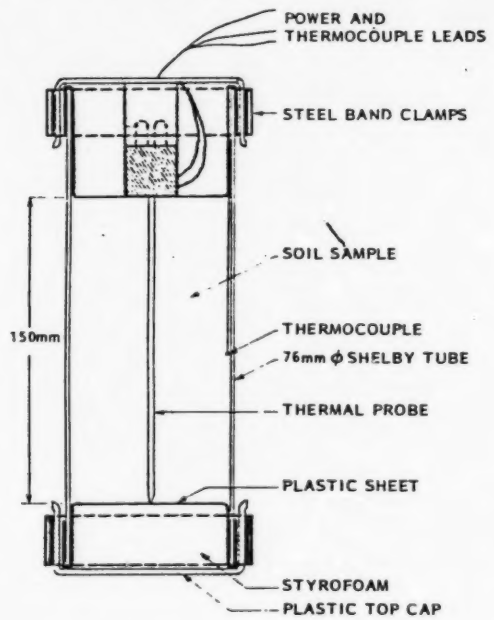


Fig. 6 Shannon and Wells thermal diffusivity test using a Shelby tube sample

The samples are allowed to equilibrate at a constant elevated temperature overnight in an oven. This temperature should only be about 8 C° above the ambient room temperature. If the samples are preheated to too high a temperature the thermal gradients induced after their immersion in the water bath would cause moisture migration in the soil sample and the attendant convection of heat would disrupt the measurement of thermal diffusivity. An 8 C° rise in temperature is enough to provide good definition of the cooling curve for the Shannon and Wells analysis.

The warm samples are transferred to a constant room temperature circulating water bath and the temperature and time of the thermal probe are monitored. The resultant plots of temperature vs log time (Fig. 7) are analyzed by the theory of Shannon and Wells (1947) to calculate the thermal diffusivity.

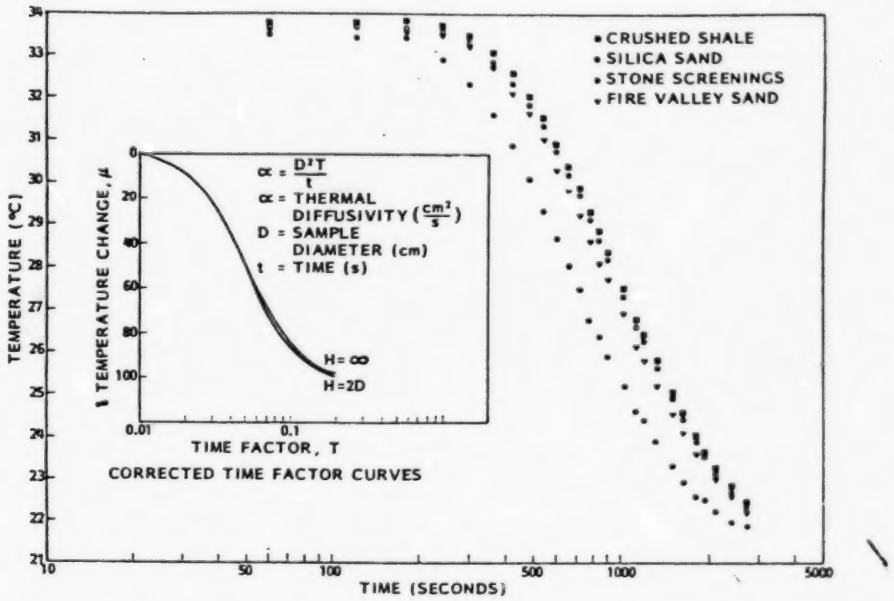


Fig. 7 Shannon and Wells thermal diffusivity test on dry soils.

TABLE 1 Shannon and Wells Test Results

Dry Soil	Time for 50% Change in Temperature(s) t	$\alpha = \frac{D^2T}{t}$ $(\frac{cm^2}{s})$	γ_d $(\frac{g}{cm^3})$	ρ $(\frac{°C\text{-}cm}{W})$	$c = \frac{1}{\rho\alpha\gamma_d}$ $(\frac{J}{g\text{-}°C})$
Crushed Shale	990	0.0025	1.9908	254	0.79
Silica Sand	960	0.0026	1.8339	300	0.70
Fire Valley Sand	910	0.0027	1.8113	264	0.77
Stone Screenings	710	0.0035	2.1609	127	1.04

*Diameter (D) = 7.0 cm, Time Factor (T) for 50% = 0.05, D^2T = 2.45

Thermal resistivity (ρ) and thermal diffusivity (α) are related by the expression:

$$C = \frac{1}{\rho\alpha} \tag{8}$$

where C is the volumetric heat capacity.

For a dry soil

$$C = \gamma_d \cdot c \tag{9}$$

where c is the specific heat of the soil solids.

$$\text{Thus } c = 1/\rho\alpha\gamma_d. \tag{10}$$

The experiment was performed on four representative dry soil samples for the measurement of both the thermal diffusivity and resistivity. Table 1 summarizes the thermal diffusivity and the specific heat values calculated from the above equation. The specific heat of soil solids can be generally considered to be in the range of 0.8 [J/g-°C] (Shannon and Wells, 1947). The experimental results fall very close to this (with the exception of stone screenings) indicating that the two thermal property measurements give reasonable and compatible results.

FIELD TESTING

Field probes have been used in 1 and 2 m lengths and diameters of 6, 10, and 25 mm. For the larger diameter probes, the deviation from the theory becomes greater and more emphasis has to be placed on probe calibration and applying necessary corrections to the results.

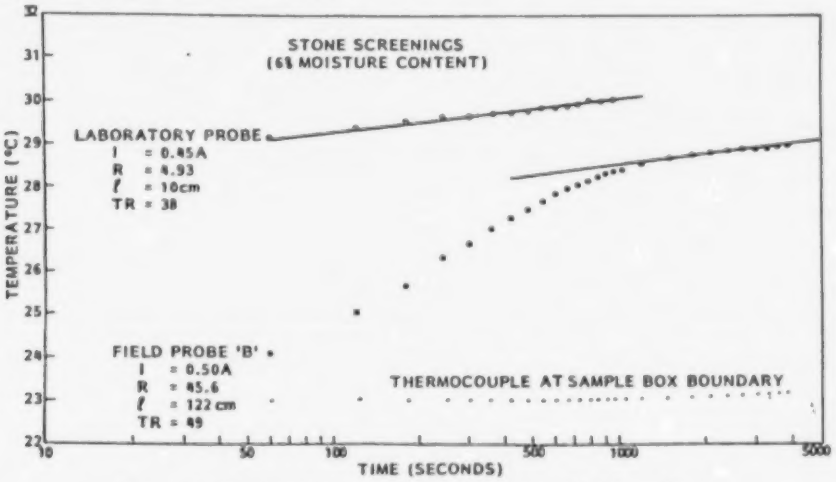


Fig. 8 Calibration of 25 mm diameter field probe

The field probes will contain quite a large volume of filler material and therefore the heat capacity of the probe will be rather significant. Combined with the thermal contact resistance effects this will extend the initial transient time significantly. Certain 25 mm diameter probes when checked in the laboratory were found to have an initial transient time in the order of 1500 seconds (Fig. 8). In such a case the thermal resistivity test must be extended to between 2000 and 3000 seconds and only the points after 1500 seconds used for thermal resistivity calculations. Thermal diffusivities calculated from such data by the intercept method are not valid.

In addition to a large initial transient time, the probe thermal properties (resistivity, heat capacity) can affect the measured soil thermal resistivity. For instance, the 25 mm diameter probes, when calibrated against laboratory probes gave 20% higher values for the thermal resistivity. Thus a 20% correction had to be applied to field data.

For in situ tests the maximum test time is no longer of concern since there are no radial boundaries to limit test time. Thus it is possible to run a thermal stability test (Boggs and others, 1980). This involves a standard low power thermal resistivity test, immediately followed by another run of the same duration, only with ten times the power (Fig. 9). In a thermally unstable soil the high heat run will induce significant moisture migration away from the probe thus increasing the thermal resistivity. In a thermally stable backfill soil, the thermal resistivity values from the low and high power runs will be similar.

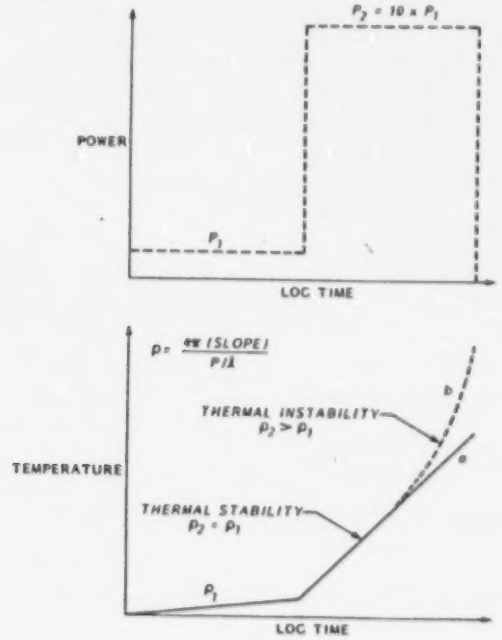


Fig. 9 Two-power thermal resistivity measuring technique for the determination of thermal stability

The field probe must be inserted carefully to assure good probe to soil thermal contact and minimal disturbance of the natural soil. In sufficiently soft soils (ie soft clays), a 1 m long 10 mm diameter probe can be inserted by hand. In general, a guide jig and pre-drilled pilot hole are necessary. The guide must be securely pegged into the ground so as not to move and distort the hole. Even when pushing a probe, a suitable guide is desirable to keep the probe in line and minimize hole distortion caused by side-to-side movement of the probe.

In stiff soils a probe cannot be pushed and a pilot hole must be drilled. In this case a guide is used to keep the long-shafted drill in line (simply a hand held power drill). The drill should only be advanced the length of the bit before the flutes are cleaned so that the drill is cutting and removing material rather than

pushing and displacing the soil. Drill bits should be no larger than the probe diameter and preferably slightly undersized. The smallest diameter pilot hole should be drilled which permits the probe to be inserted, so that the good probe-soil contact is achieved. In soil with coarse angular particles, the probe may catch and cannot be inserted at all. In this case, the pilot hole must be drilled to the exact size. The probe should never be hammered since at worst it may be damaged and at best may disturb the resident material and result in a distorted hole with poor probe-soil contact. To prevent bending the probe, a hand-held gripper can be used to push the probe from about 150 mm above the soil surface. If necessary, a hydraulic jack may be required (Cameron and Brookes, 1960).

The selection of drill size and the insertion technique for different soil conditions comes with practical experience. In homogeneous fine grained soils or those containing only fine gravel fractions the above techniques are successful. In soils containing coarse gravel particles or cobbles (glacial tills) that cannot be dislodged by drilling, probe insertion can turn out to be a trial and error procedure. Several pilot holes may be necessary before one goes through without striking an obstruction. In cases where a probe is only partially inserted, a valid run may be carried out for the embedded thermocouples, but care must be taken not to overheat the protruding part of the probe.

One metre flights of probe can, in general, be inserted with minimal effort and distortion of the hole, resulting in good probe-soil thermal contact. Longer lengths usually result in considerably more disturbance of the hole and increased difficulty with hand pushing methods, due to increased soil friction on the sides of the probe and crookedness inherent to long probes. Thus the use of one-meter probes is convenient except where measurements are required at greater depths. For great depths, a longer probe with an active length of only 1 m can be advanced in flights of 1 m. Field experience indicates that a 10 mm diameter probe is the smallest size that offers sufficient rigidity for the rigours of field use. A smaller diameter, such as 6 mm, is too flexible and causes hole distortions during predrilling or pushing, resulting in substantial contact resistance. The 6 mm probe may be used to advantage in cases, such as tills, where a thinner probe may slip in more easily between the larger stones or in cohesive clays where side friction makes the pushing of the larger diameter probes difficult.

CONCLUSIONS

The transient thermal probe is a relatively quick , versatile method of measuring the soil thermal properties. Valid results can be obtained if the test conditions approximate, as closely as possible, the constant power, line source of heat in an infinite medium theory. The probe to soil contact resistance, probe heat capacity, and the sample boundary conditions, if not accounted for, can significantly affect the test results.

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DISCUSSIONS

W.Z. Black, Georgia Institute of Technology *In Figure 5 you identify "critical moisture" contents for several soils, implying that soil will be thermally stable when its moisture content is above the "critical" value. The research effort at Georgia Tech and Georgia Power has identified the heat input per unit length as also being an important parameter influencing the thermal stability. We are afraid that many who are not skilled in making stability measurements will use your simplified stability model and will regard the moisture content of the soil as the only factor which needs to be considered.*

From our research work, for example, we have shown that Georgia clay can be unstable for moisture contents up to 20% which is well above the value that you have identified as the "critical moisture" content. This illustrates the danger of using a single moisture content as an important stability parameter simply because it is located near the knee of the rho vs moisture curve.

Would you comment on how you can use the single value for critical moisture content when, in addition, the stability is also a function of the heat generated within the cable.

J.E. Steinmanis *In general, the thermal stability of a soil is a function of the thermohydraulic properties of the soil, which depend on moisture, time, and heat input. Soils suitable as thermal backfills do exhibit a stable thermal resistivity above a "critical" moisture content, for any realistic power dissipation. The thermal resistivity versus moisture content curve (which can be fairly easily determined by stage-drying, two-power tests on laboratory samples (Boggs and others, 1980)) for these soils has a sharp knee and therefore the "critical" moisture can be clearly defined. In a cable installation, good thermal soil is placed near the cable, therefore the simple concept of a "critical" moisture can be used as the indication of the thermal stability of the system.*

For thermally unsuitable soils, such as Georgia clay, the thermal resistivity increases fairly steadily with decreasing moisture and the thermal stability depends on the heat flux. In this case more complex testing, that will consider both the initial moisture content and power dissipation, would have to be done to characterize the thermal stability of the soil. But in general this is not necessary since the native soil outside the backfill experiences such a low heat flux that thermal drying and instability will not occur.

In Figure 5 a relative "critical" moisture content is indicated for the poor thermal soils only for the purpose of comparison with the good thermal soils. A low "critical" moisture and a sharp bend in the curve indicates a good thermal backfill.